# U.S. GODAE: Global Ocean Prediction with the Hybrid Coordinate Ocean Model (HYCOM)

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## LONG-TERM GOALS

A broad partnership of institutions is collaborating in developing and demonstrating the performance and application of eddy-resolving, real-time global and basin-scale ocean prediction systems using the HYbrid Coordinate Ocean Model (HYCOM). These systems are to be transitioned for operational use by the U.S. Navy at both the Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, MS, and the Fleet Numerical Meteorology and Oceanography Center (FNMOC), Monterey, CA, and by NOAA at the National Centers for Environmental Prediction (NCEP), Washington, D.C. The systems will run efficiently on a variety of massively parallel computers and will include sophisticated, but relatively inexpensive, data assimilation techniques for assimilation of satellite altimeter sea surface height (SSH) and sea surface temperature (SST) as well as in-situ temperature, salinity, and float displacement.

The partnership represents a truly broad spectrum of the oceanographic community, bringing together academia, federal agencies, and industry/commercial entities, spanning modeling, data assimilation, data management and serving, observational capabilities, and application of HYCOM prediction system outputs. The institutions participating in this Partnership have long histories of supporting and carrying out a wide range of oceanographic and ocean prediction-related research and data management. All institutions are committed to validating an operational hybrid-coordinate ocean model that combines the strengths of the vertical coordinates used in the present generation of ocean models by placing them where they perform best. This collaborative partnership provides an opportunity to leverage and accelerate the efforts of existing and planned projects, in order to produce a higher quality product that will collectively better serve a wider range of users than would the individual projects. In addition to operational eddy-resolving global and basin-scale ocean prediction systems for the U.S. Navy and NOAA, respectively, this project offers an outstanding opportunity for NOAA-Navy collaboration and cooperation ranging from research to the operational level.

This effort is part of a 5-year (FY04-08) multi-institutional National Ocean Partnership Program (NOPP) project which includes the Florida State University (E. Chassignet), U. of Miami (G. Halliwell, M. Iskandarani, T. Chin, A. Mariano, Z. Garraffo, A. Srinivasan), NRL/STENNIS (H. Hurlburt, A. Wallcraft, J. Metzger, B. Kara, J. Cummings, G. Jacobs, H. Ngodock, C.A. Blain, P. Hogan, J. Kindle), NAVOCEANO (F. Bub), FNMOC (M. Clancy), NRL/MONTEREY (R. Hodur, J. Pullen, P. May), NOAA/NCEP/MMAB (H. Tolman, C. Lozano), NOAA/NOS (F. Aikman), NOAA/AOML (C. Thacker), NOAA/PMEL (S. Hankin), Planning System Inc. (O.M. Smedstad), NASA-GISS (R. Bleck), SHOM (R. Baraille), LEGI (P. Brasseur), OPeNDAP (P. Cornillon), U. of

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## OBJECTIVES

The partnership is addressing the Global Ocean Data Assimilation Experiment (GODAE) objectives of three-dimensional (3D) depiction of the ocean state at fine resolution in real-time and provision of boundary conditions for coastal and regional models. It will also provide the ocean component and oceanic boundary conditions for a global coupled ocean-atmosphere prediction model. It will make these results available to the GODAE modeling community and general users on a 24/7 operational basis via a comprehensive data management strategy.

## APPROACH AND WORK PLAN

HYCOM development is the result of collaborative efforts among the Florida State University, University of Miami, and the Naval Research Laboratory (NRL) as part of the multi-institutional HYCOM Consortium for Data-Assimilative Ocean Modeling. This effort was funded by the National Ocean Partnership Program (NOPP) to develop and evaluate a data-assimilative hybrid isopycnal-sigma-pressure (generalized) coordinate ocean model (Bleck, 2002; Chassignet et al., 2003; Halliwell, 2004). More details can be found at http://www.hycom.org.

While HYCOM is a sophisticated model, including a large suite of physical processes and incorporating numerical techniques that are optimal for dynamically different regions of the ocean, data assimilation is still essential for ocean prediction a) because many ocean phenomena are due to flow instabilities and thus are not a deterministic response to atmospheric forcing, b) because of errors in the atmospheric forcing, and c) because of ocean model imperfections, including limitations in resolution. One large body of data is obtained remotely from instruments aboard satellites. They provide substantial information about the ocean's space-time variability at the surface, but they are insufficient by themselves for specifying the subsurface variability. Another significant body of data is in the form of vertical profiles from XBTs, CTDs, and profiling floats *(e.g.,* ARGO). Even together, these data sets are insufficient to determine the state of the ocean completely, so it is necessary to exploit prior knowledge in the form of statistics determined from past observations as well as our understanding of ocean dynamics. We combine all sources of information synergistically to produce the best possible depiction of the evolving ocean. Several techniques for assimilating data into HYCOM are either in place or under development.

## RESULTS

We report here on progress made in FY09 (one-year extension of the original award) by QinetiQ North America in collaboration with FSU on the HYCOM 1/12° global ocean prediction system and by FSU on the management of ocean model outputs.

### a) Global 1/12°ocean prediction system

**NCODA Implementation:**

The Navy Coupled Ocean Data Assimilation (NCODA), (Cummings, 2005), is the assimilation component in HYCOM. The NCODA system is a fully three-dimensional multivariate optimum interpolation system. The three-dimensional ocean analysis variables include temperature, salinity, geopotential, vector velocity components and in support of HYCOM, a new analysis variable that corrects the model layer pressure of the hybrid vertical coordinates. An analysis of sea ice concentrations is also a part of the NCODA analysis. The NCODA horizontal correlations are multivariate in geopotential and velocity, thereby permitting adjustments (increments) to the mass fields to be correlated with adjustments to the flow fields. The velocity adjustments are in geostrophic balance with the geopotential increments, and the geopotential increments are in hydrostatic agreement with the temperature and salinity increments. Either the Cooper and Haines (1996) technique or synthetic T & S profiles (Fox et al., 2002) can be used for downward projection of SSH and SST. Experiments using the two methods showed that the synthetic approach gave the best results when the model was compared to unassimilated temperature profiles. Two changes to the assimilation methodology were implemented. One modification is to increase the time window of the *in-situ* profile observations used in assimilation from ±12 hours to -12 days through +12 hours of the analysis time. The longer time window allows such observations to have a greater influence on successive ocean analyses, but the depth-varying weight given to each profile diminishes the older it becomes. Under the old methodology, a profile is only incorporated into the analysis one time. If on the next day an altimeter pass indicated a significant SSH change, a synthetic MODAS profile would be generated that would essentially erase the previous day's observation. An observed profile should more accurately reflect the subsurface T and S structure than a synthetic profile, even if it is a few days old, Thus observed profiles are now favored over synthetic profiles. A second modification to the assimilation methodology is the use of the ocean model's mixed layer depth (MLD) to modify and more accurately represent the vertical structure of the synthetic MODAS profiles, which tend to have a shallow MLD bias. Below the forecast MLD the modified synthetic relaxes back to the original T and S profile using a 10 m relaxation scale. This leads to a sharper transition at the base of the mixed layer.

The NCODA analysis is split into the seven sub domains shown in Figure 1. The regions covering the Mercator part of the model domain follows the natural land boundaries between the ocean basins. Each domain is run on a fraction of the total number of available processors so that each domain finishes at about the same time.

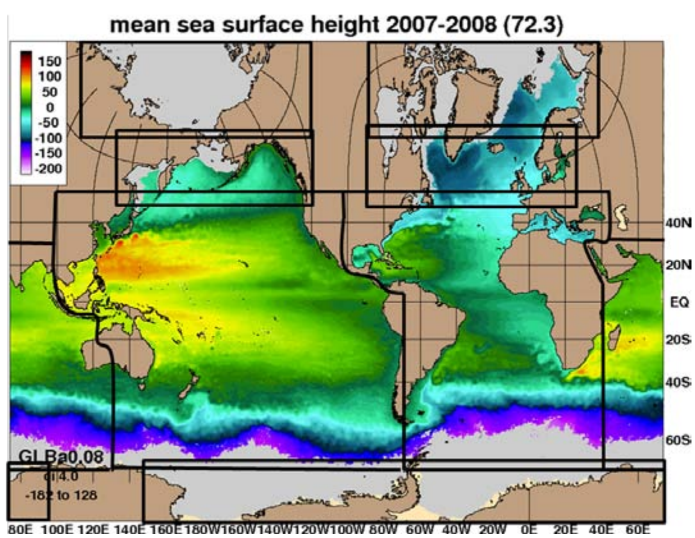



**Figure 1.** The figure shows the SSH field from the 1/12º Global HYCOM domain with the 7 regions where the Mercator part of the domain is split into the three ocean basins using the natural land boundaries.

**1/12º Global HYCOM:**

The 1/12º global HYCOM source code has had two significant modifications. The first is a change in the vertical remapping scheme (remapping between z-levels and hybrid coordinates) within the hybrid grid generator (hybgen). Previously the piecewise parabolic method (PPM) was used but this is changed to a weighted essentially non-oscillatory (WENO)-like PPM scheme for increased accuracy. The second change is in hybgen when there is a too-light layer on top of a too-dense layer, i.e. when both layers would like to gain mass at the expense of each other. Previously hybgen chose each layer half of the time, but in practice the thicker of the two layers tended to gain mass and over time, the thinner layer tended to become very thin and stay that way. Now the thinner of the two layers always gains mass from the thicker layer, greatly reducing this tendency for layers to collapse.

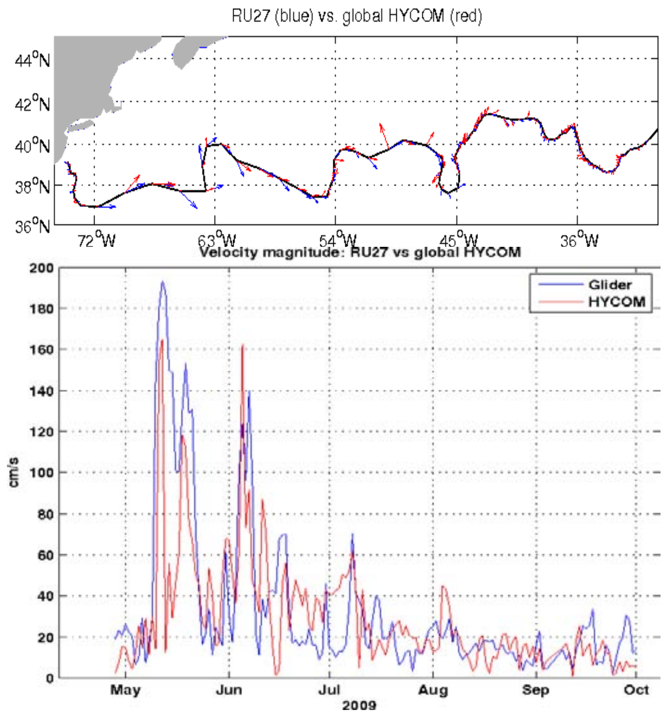
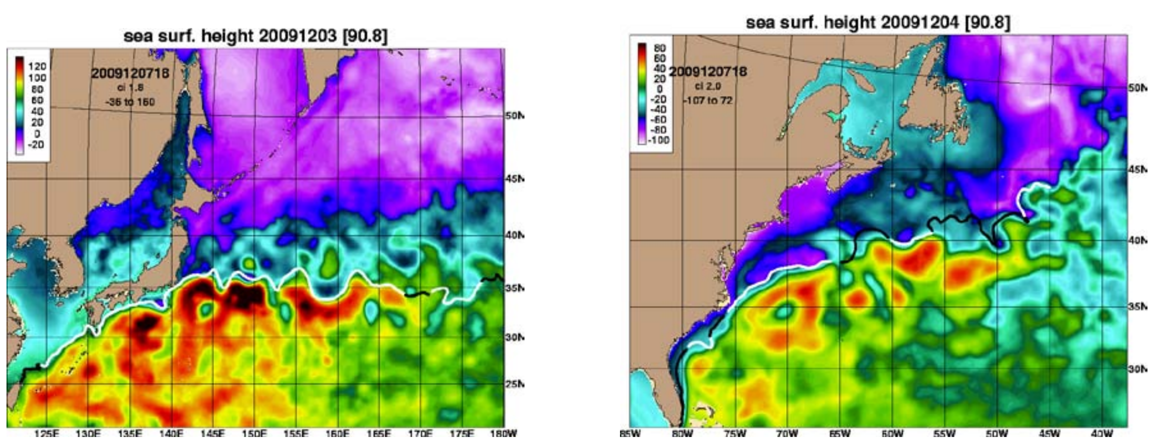



**Figure 2.** RU27 glider path (black line) and 150 m averaged current vectors (RU27 – blue arrows, HYCOM – red arrows) sampled once per day nearest 00Z (top panel). One hundred fifty meter depth averaged speed (cm/s) as a function of time (bottom panel) using the same color scheme.

The validation tasks performed this year include a temperature vs. depth error analysis and an acoustical proxy (mixed layer depth, sonic layer depth, below layer gradient and deep sound channel) error analysis. In addition, it focused on: a) the two systems as being providers of boundary conditions (BCs) to a higher resolution nested Relocatable NCOM, b) an examination of the 14-day forecast skill relative to climatology and persistence of the temperature (T) versus depth, c) an examination of the 14-day forecast skill of the acoustical proxy variables, d) an examination of 14-day forecast skill of sea surface height (SSH) and sea surface temperature (SST), e) a comparison of the system's ability to track drifting buoys and f) the ability of the systems to simulate ocean velocity against unassimilated current measurements. These comparisons are performed using results from a new hindcast with the above mentioned improvements to the system as well as results from the real time system. An example of the comparison of the upper ocean velocity field is shown in Figure 3 and Table 1. During the summer/fall of 2008 and 2009, the Coastal Ocean Observing Lab at Rutgers University attempted two trans-Atlantic flights using Slocum gliders. These began off the U.S. East coast and traveled eastward using the Gulf Stream as a tail current to speed their progress (http://rucool.marine.rutgers.edu/atlantic/index.html). The glider shown here is RU27 which began on 27 April 2009. The glider returns average currents in the top 150 m of the ocean. Because of the shallow dive extent, T and S were not assimilated into the HYCOM system. The glider makes several dives per day and the analysis here uses glider observations closest to 00Z which are compared against the nearest model gridpoint also at 00Z and averaged over comparable depths. Figure 2 depicts the glider paths and current vectors sampled once per day and the average speed. Vector correlation [u·v / sqrt((u·u) * (v·v))] is shown in Table 1

| Vector correlation: RU27 vs. HYCOM | | | | | |
|---|---|---|---|---|---|
| May | June | July | August | September | All |
| .48 | .48 | .61 | .19 | .56 | .47 |

**Table 1**: Vector correlation between the unassimilated glider and HYCOM.




(a) (b)

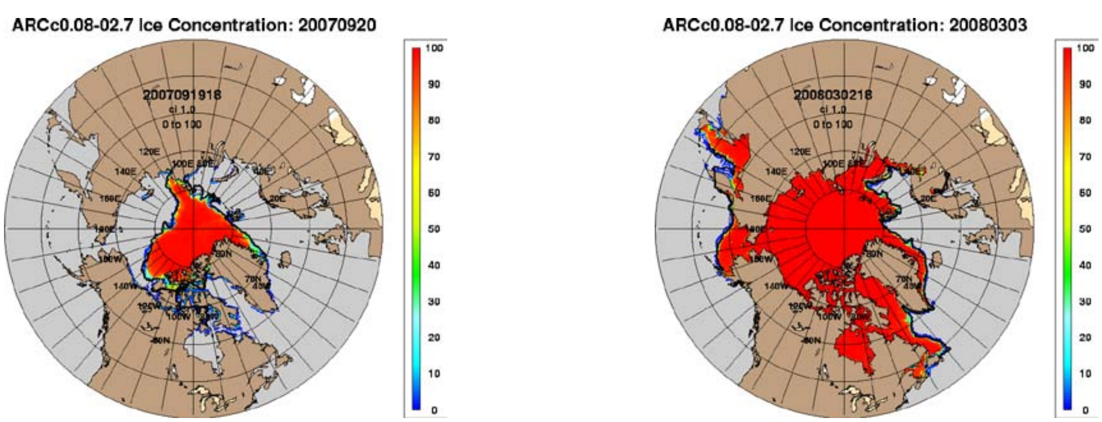
**Figure 3**. The SSH field from the real time 1/12º Global HYCOM domain (a) on 3 December 2009 in the Kuroshio region and (b) on 4 December 2009 in the Gulf Stream region. The black line represents the frontal analysis of MCSST observation performed at the Naval Oceanographic Office. A black line represents data more than four days old.

The pre-operational nowcast/forecast system using the 1/12º global HYCOM continues to run in real-time. It started running in near real time on 22 December 2006 and in real-time on 16 February 2007. The real time system was moved to the new Cray XT5 at the Naval Oceanographic Office and is now running on 619 processors (24 nodes) using a part of the operational allocation on the machine. The daily run consists of a 5 day hindcast and a 5 day forecast and takes about ~14 wall clock hours. The NCODA analysis is performed at 18Z and the model is incrementally updated over the next 6 hours so that the data from the 18Z analysis is in the model at the 00Z nowcast. The real-time web page showing the results from the system can be found on the HYCOM consortium web page, **http://www.hycom.org**. The model output is also available through this web site. The model is routinely compared to both independent observations and observations that are used in the assimilation. An example of an independent observation comparison can be seen in Figure 3a-b. These figures show the SSH in the Kuroshio and Gulf Stream region, respectively. The white/black line represents the frontal analysis of MCSST observations performed at the Naval Oceanographic Office. A black line represents data more than four days old. The model is able to accurately depict the frontal position in these regions, showing most of the meanders indicated in the observations.

Additional information about the validation of the nowcast/forecast system can be found in Metzger et al. (2008) and Metzger et al. (2009).

**CICE:**

The coupling between HYCOM and the Los Alamos ice model (CICE) has been tested in an Arctic Cap version of HYCOM. CICE and HYCOM are coupled via the Earth System Modeling Framework (ESMF). The NCODA sea ice analysis was used to update the ice concentration in the ice model. Experiments showed that the assimilation of the analyzed ice concentration had a very positive impact on the positioning of the ice edge. Figure 4a-b shows an example from a hindcast experiment. In figure 2a the ice thickness for 20 September 2007 is shown. The black line is an independent ice edge analysis performed at the National Ice Center using SSMI observations. The minimum ice concentration observed in the fall of 2007 is clearly represented in the model. Figure 4b shows the ice concentration on 3 March 2008. The ice has grown back and matches the observed ice edge.




(a) (b)

**Figure 4**. Ice concentration from CICE is shown. The black line represents the ice edge analysis performed at the National Ice Center using SSMI observations. (a) shows the ice concentration on 20 September 2007 and (b) the ice concentration on 3 March 2008.

**b) <u>Data management:</u>**

The main goal was to develop and implement a comprehensive data management and distribution strategy that allows easy and efficient access to HYCOM-based ocean prediction system outputs to (a) coastal and regional modeling sites, (b) to the wider oceanographic and scientific community including climate and ecosystem researchers, and (c) the general public especially students in middle and high schools. The basic idea consists of the setup of a web server that acts as a gateway to backend data management, distribution and visualization applications. These applications enable end users to obtain a broad range of services such as browsing of datasets, gif images, NetCDF files, FTP request of data etc. The HYCOM Data Sharing System is built upon two existing software components: the Open Project for a Network Data Access Protocol (OPeNDAP) and the Live Access Server (LAS). These tools and their use to distribute the data are described below. In the current setup, the OPeNDAP component provides the middleware necessary to access distributed data, while the LAS functions as a user interface and a product server. The abstraction offered by the OPeNDAP server also makes it possible to define a virtual data set that LAS will act upon, rather than physical files. An OPeNDAP "aggregation server" utilizes this approach to append model time steps from many separate files into virtual datasets.

The HYCOM Data service has been in operation for the last five years and has seen a steady increase in the user base. A Storage Area Network (SAN) consisting of three servers consisting of 4 AMD dual core Opteron CPUs attached over fibre channel to 130 TB of SATA based storage has been recently purchased. In this system, the servers are configured in a high availability mode and runs a Global file system which will allow concurrent read/write requests from all the attached 24 CPU's. The server design and overall operational philosophy includes high availability and high reliability features to allow for uninterrupted use.

## IMPACT/APPLICATIONS

Three-dimensional (3D) depiction of the ocean state at fine resolution in real-time and provision of boundary conditions for coastal and regional models in the context of the Global Ocean Data Assimilation Experiment (GODAE).

## TRANSITIONS

The 1/12° global HYCOM system is running in real time, and was transitioned to NAVOCEANO at the end of FY08 with operational testing is planned in FY10.

## RELATED PROJECTS

This is a highly collaborative NOPP project. Additionally, the project is receiving grants of super computer time from the DoD High Performance Computing Modernization Office.

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